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**Research Paper
RM-254**

Natural Regeneration of Engelmann Spruce after Clearcutting in the Central Rocky Mountains in Relation to Environmental Factors

Robert R. Alexander

Abstract

Successful natural regeneration of Engelmann spruce in small clearcut openings depends on weather and aspect and is modified by cultural treatments. Small clearcut openings (1–2 ha) can be successfully regenerated on north aspects with mineral soil seedbeds and shade. On south aspects, shade is absolutely essential for any survival. However, successful natural regeneration is not likely regardless of cultural treatments. Drought is the most serious cause of mortality; but clipping by birds, frost heaving (north aspect), heat girdle (south aspect), and snowmold (north aspect) caused significant losses.

Cover Photo.—The 1969 replication of seedbed treatments on the north aspect, Fraser Experimental Forest, Colorado.

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Robert R. Alexander, Chief Silviculturist
Rocky Mountain Forest and Range Experiment Station[1]

[1]Headquarters is in Fort Collins, in cooperation with Colorado State University.

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The uncertainty of successful Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.) natural regeneration after clearcutting spruce-subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) forests is a major management concern in the central Rocky Mountains (Alexander 1974). Three basic requirements for natural regeneration success are: (1) an adequate supply of seed, (2) a suitable seedbed, and (3) an environment compatible with germination and survival (Roe et al. 1970). Research and observations most often identified environmental factors as the most limiting to Engelmann spruce natural regeneration success (Noble and Alexander 1977). This study, started in 1968, was designed to identify limiting factors and determine modifications in cultural practices needed to provide suitable environments for spruce regeneration. This paper includes data from 1973 through 1982, and from a published 5-year progress report (Noble and Alexander 1977).

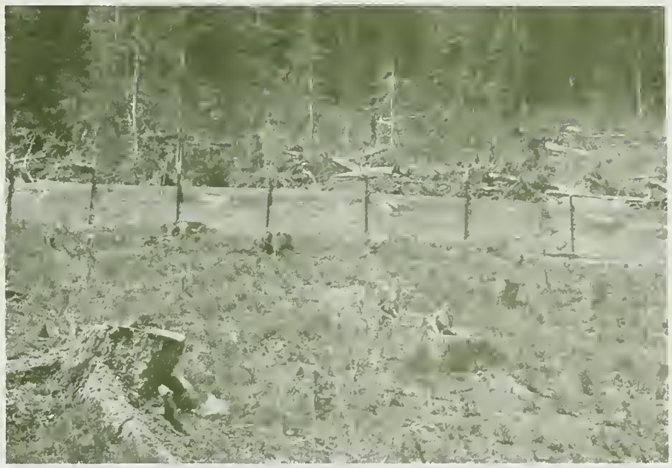

Figure 1.—Study area on the north aspect, after rodent exclosures were installed, but before seedbed treatments were in place.

STUDY AREAS

Field observations were made from 1968 through 1982, on the Fraser Experimental Forest, in central Colorado, on two areas approximately 7.2 km apart. Both study areas are at about 3,230 m elevation—one on a north aspect and the other on a south aspect. Slope is 10–12% on the north aspect and 12–15% on the south aspect. Both study areas are enclosed within 30.5- × 33.5-m hardware cloth rodent exclosures (Noble and Alexander 1975) in the center of 1.46-ha-square clearcut openings (fig. 1). The opening on the north aspect was cut in 1956, the south aspect in 1967. The hardware cloth generally excluded deer mice (*Peromyscus maniculatus* Wagner), red-backed voles (*Clethrionomys gapperi* Vigors), mountain voles (*Microtus montanus* Peale), western chipmunks (*Eutamias minimus* Bachman), and pine squirrels (*Tamiasciurus hudsonicus fremonti* Audubon and Bachman); but not pocket gophers (*Thomomys talpoides* Richardson) or birds that feed on tree seed, such as the grey-headed junco (*Junco caniceps* Woodhouse) (Noble and Shepperd 1973). Additional control of rodent populations was initially obtained by poisoning; one tablespoon of 1080-treated oats or gophicide treated wheat was placed in a bait can with an opening only large enough to allow access to small mammals. Bait cans were placed on a 15.2- × 15.2-m grid across the clearcut openings. Poisoning was discontinued after 1970, when the U.S. Environmental Protection Agency prohibited the use of rodenticides. Trapping was used thereafter to control small mammals.

The original stands were spruce-fir or mixed spruce-fir and lodgepole pine (*Pinus contorta* Dougl. ex Loud.), typical of the forests on the west side of the Continental Divide. These old-growth stands were situated on sites of moderate productivity (site index 60 to 70) (Alexander 1967). The habitat type is *Abies lasiocarpa/Vaccinium scoparium*, the most common spruce-fir habitat type in Colorado. The *Vaccinium* union does not compete as severely with tree seedlings as undergrowth vegetation does in other habitat types.

The climate of the Fraser Experimental Forest is also typical, and can be characterized as cold and humid (Haeffner 1971). Mean annual temperature is 0.6° C with extremes of −40° C and +32° C. Annual precipitation averages 58 cm, with a range of 46 to 86 cm. Approximately two-thirds of the precipitation falls as snow from October through May.

Soils on both areas are gravelly, sandy loams developed in place from coarse-textured material weathered from mixed gneisses and schists (Retzer 1962). Average depth to the C horizon is 30–40 cm on the north aspect and 50 to 60 cm on the south aspect. Laboratory analyses of the soils showed the following texture composition and soil moisture content, respectively (Noble 1972):

	North aspect (%)	South aspect (%)
Sand	56	54
Silt	34	30
Clay	10	16
1/3 bar tension	18	15
15 bar tension	9	8

METHODS

Experimental Design

The design was a two-by-two factorial replicated over 10 years, in randomized blocks. A set of twelve 1-m^2 seedbeds (four seedbed treatments replicated three times) was prepared on each aspect, each year from 1968 through 1977.

Seedbed Treatments

The four seedbed treatments were scarified-shaded, scarified-unshaded, unscarified-shaded, and unscarified-unshaded. Plots were scarified by hand to remove all material to mineral soil. Scarification simulated scalping with a dozer blade. Overhead shade was provided by wooden frames made from 5-cm-wide furring strips alternated with 5-cm spaces, elevated 20 to 25 cm above the ground on metal framing. Slots of the shade frames were oriented in a north-south direction to provide alternate periods of shade and sunlight (fig. 2).

Seeding

The Engelmann spruce seed used in this study was collected on the Fraser Experimental Forest. New collections were made only when stored seed viability, based on laboratory germination tests, dropped to less than 60%. In late September of each year (1968 to 1977), an estimated 125 viable seeds were evenly broadcast on each seedbed. The total number of seeds sown per seedbed each year varied from 165 to 210, depending on viability. The seeds were not covered, because the intent was to simulate natural regeneration. The number of seeds sown corresponds to 1,235,000 sound seeds per hectare, which can be expected from a heavy natural seedfall (Alexander et al. 1982). Plots were placed at least 45 m from the nearest timber edge to minimize the input of seed from adjacent timber stands.

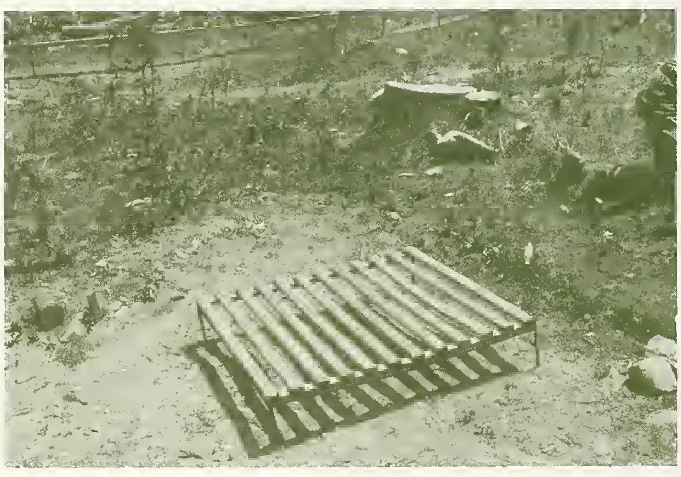

Figure 2.—Shade frame in place on north aspect scarified-shaded treatment.

Environmental Measurements

Air temperatures and relative humidity were recorded from June to October each year, on each aspect, using hygrothermographs and maximum-minimum thermometers housed in standard Weather Bureau shelters (fig. 3). Periodically, air temperatures also were measured in full sunlight at the standard height of 1.37 m, using temperature thermistors and a circuit bridge. Wind velocity at 1.83 m was measured with recording anemometers; precipitation was measured gravimetrically with 20.3-cm raingages exposed without funnels or tubes.

Total horizontal incident radiation was obtained from a pyroheliometer located in a level opening between the two aspects but at a slightly lower elevation. These data were adjusted for slope and aspect using equations developed by Kaufmann and Weatherred (1982) to obtain potential direct beam solar irradiation, expressed as total langleys (ly) per day.

Periodically, seedbed temperatures were measured from mid-June to mid-August in 1971, 1972, and 1973, at the surface with an infrared field thermometer, and at 2.5, 5.1, 10.2, and 20.3 cm above and below the surfaces with thermistors (fig. 4). No measurements were made within 48 hours following 5.1 cm or more of precipitation to avoid variability in temperatures associated with evaporation. Data from 18 days when air temperatures were near the average maximum were used in the final tabulation. Absolute temperatures at the surface were estimated using temperature-sensitive wax tempules.

Seedling Measurements

During the first growing season after each sowing, germination, survival, and cause of mortality were recorded at least twice weekly; after the first season, survival and mortality counts were made weekly. Measurements were begun in June, when the plots were first clear of snow, and ended in October, with the onset of winter snow cover.

Data Compilation and Analysis

Environmental

To characterize the environment on each aspect, measurements of bulk-air temperatures, precipitation, net incident radiation, and wind velocity were compiled into daily, weekly, monthly, and seasonal summaries. Similar compilations were made for vapor pressure deficits (VPD) computed from relative humidities and temperatures. Precipitation and temperature also were compared with long-term weather records reported by

Haeffner (1971) for the Fraser Experimental Headquarters site at 2,743 m elevation, and approximately 7.2 km from each study site.

Soil surface and subsurface, soil profile, and air profile temperatures were summarized to characterize the microenvironment associated with seedbeds so that comparisons could be made between seedbed treatments for each aspect. Soil surface temperatures and subsurface-soil and air-temperature profiles were averaged to provide estimates of mean maximum diurnal temperatures.

Seedlings

Differences in germination each year for the 10 years of record were tested separately for each aspect by analysis of variance after arc-sin transformation. Seedbed treatments and years were the independent variables; percent germination each year the dependent variable. Orthogonal comparisons were made between treatments. The sampling unit was the individual plot total.

Differences in survival also were tested for each aspect using analysis of variance after arc-sin transformation. Seedbed treatments and years were the independent variables. The dependent variable was the percent of surviving seedlings at the end of 1 year, 5 years, and the end of the study.

RESULTS

Weather Factors

Air Temperature

Mean air temperature recorded in the weather shelters on both aspects was near normal for the 14 years of observation, varying less than 1° C from the long-term average (8.3° C) on the Fraser Experimental Forest. Temperature patterns for the months of June through October were similar on both aspects (fig. 5). Although mean temperatures during the period of observation varied about 3° C between years on both aspects, the south aspect averaged only about 1° to 1.5° C warmer than the north aspect (table 1).[2]

Figure 3.—Standard weather shelter installed on the north aspect showing hygrothermograph and max-min thermometer. Standard precipitation can is being weighed. Cup anemometer and generator in place (recorder not shown).

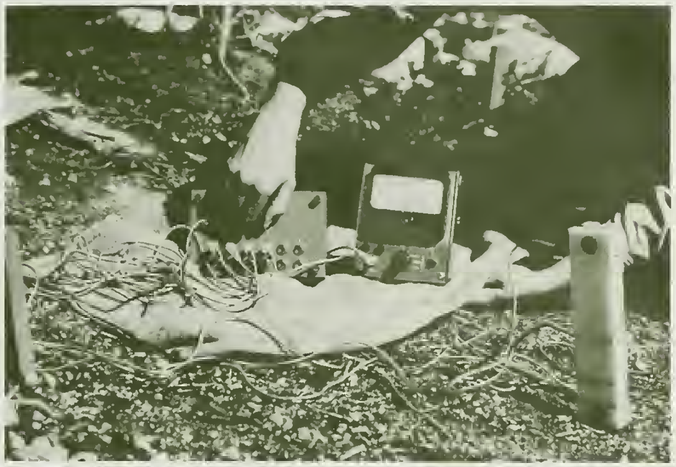

Figure 4.—Simultaneous air-temperature profiles were measured with unshielded thermistors at 2.5, 5.1, 10.2, and 20.3 cm above the surface using a tele-thermometer and switchbox.

This temperature difference and pattern occurred whether measured in the standard shelters or in the open at 1.37 m. Temperatures in the open were generally 1° C cooler at sunrise, 3–4° C warmer at noon, and about the same at sunset as was measured in the shelters.

Precipitation

Mean precipitation on both aspects was also near normal for June through October, varying less than 2 cm from the long-term average (23 cm) on the Fraser Experimental Forest. Precipitation patterns were similar on each aspect; but there was considerable variability from year to year (fig. 6). The south aspect averaged about 2 to 6 cm more precipitation than the north aspect during the months of June through October (table 1).[2]

Vapor Pressure Deficits (VPD)

VPD followed similar patterns on both aspects; but there was also considerable variability from year to year (fig. 7). Mean VPD was always slightly higher (0.5–

[2] *Mean hourly maximum, minimum, and mean air temperatures, mean monthly precipitation, average daily maximum, minimum, and mean vapor pressure deficits, net radiation, and mean daily and peak gust wind velocity are given in tables A-1 through A-5, for the months of June through October, on each aspect, for the years 1968 through 1982.*

Table 1.—Average maximum, minimum and mean for the five weather factors measured June through October

	North Aspect			South Aspect		
	max.	min.	mean	max.	min.	mean
Air temperature (° C)	14.1	1.6	7.6	14.8	3.2	8.4
Precipitation (cm)	28.6	6.4	21.9	34.4	8.6	25.0
Vapor pressure deficit (mm Hg)	12.0	5.0	8.8	12.9	5.5	9.5
Net radiation (ly/day)	554	406	480	600	446	526
Wind (km/hr)	7.2	—	2.6	10.6	—	3.3

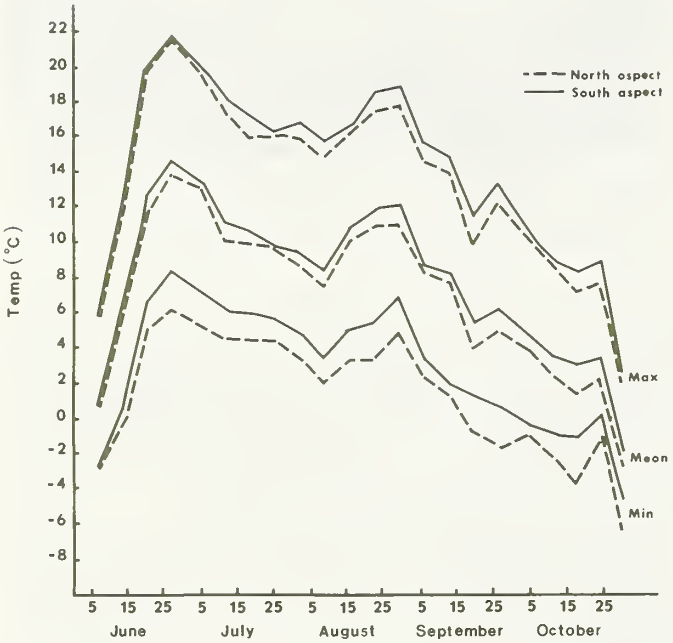

Figure 5.—Comparison of bulk-air temperatures recorded in weather shelters for the 1974 season illustrated characteristic season pattern between north and south aspects.

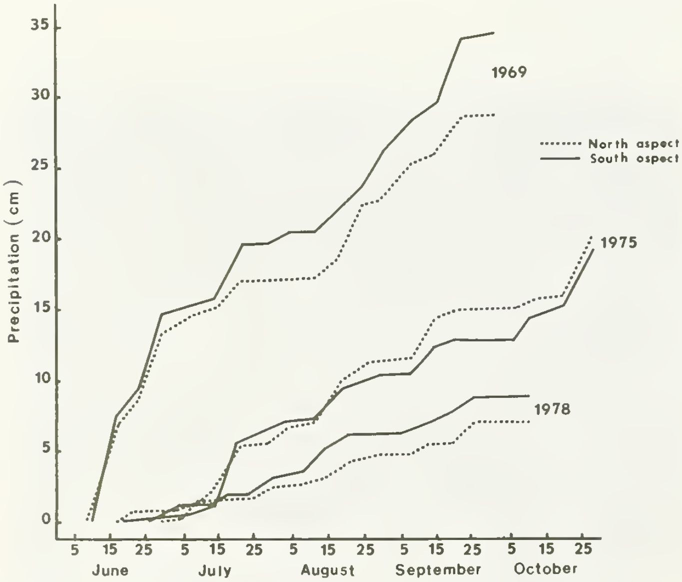

Figure 6.—Seasonal precipitation patterns for above average, average, and below average years on the north and south aspects.

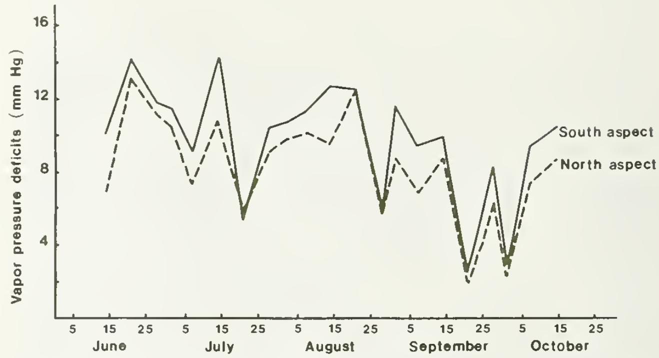

Figure 7.—Comparison of vapor pressure deficits for the 1971 season illustrates the characteristic seasonal pattern between north and south aspects.

Figure 8.—Comparison of net incident radiation for the 1975 season illustrates the characteristic seasonal pattern between north and south aspects.

Figure 9.—Comparison of average hourly wind velocity for the 1979 season illustrates the characteristic seasonal pattern between north and south aspects.

1.0 mm Hg) on the south aspect (table 1).[2] The monthly average VPD was generally highest in July and lowest in October.

Net Incident Radiation

The south slope received about 9% more net incident radiation per growing season, averaging 46 ly per day more than on the north aspect or accumulating 6,762 ly more during the months of June through October. The highest daily average was for June on the north aspect; thereafter, the radiation decreased, particularly on the north aspect (fig. 8). Maximum average daily growing season radiation was in June 1971 on the north aspect (781 ly) and the minimum (127 ly) in October of 1974 on the north aspect (table 1).[2]

Wind Velocity

Both aspects were well ventilated and wind patterns were similar (fig. 9); but average wind velocity and peak gusts were higher on the south aspect, especially in late summer and fall (table 1).[2] The wind data also indicated a typical mountainous wind pattern—a slow downslope cold-air drainage during the night, with a morning upslope reversal, generally followed by gusty afternoon winds.

Seedbed Temperatures

Surface temperatures were affected by seedbed type, shade and aspect (table 2). Unshaded duff surfaces had the highest temperatures on both aspects. Average maximum surface temperatures on the south aspect reached 60° C by 10 a.m. (MST) and were above the scale of the instrument until about 3 p.m. Temperature sensitive wax tempules indicated absolute maximums between 79° and 83° C. On the north aspect, average unshaded duff surface temperatures reached 53° C by 11 a.m., occasionally exceeded the range of the instrument, but averaged about 55° C until 2 p.m. Absolute maximum temperatures were between 63° and 73° C. Average maximum surface temperatures for unshaded mineral soil on both aspects were at least 12° C cooler than unshaded duff surfaces.

Shade reduced maximum surface temperatures 6–8° C on both aspects (table 2). Furthermore, shaded duff surfaces on the north aspect were 2° C cooler than on the south aspect, and shaded-mineral soil surfaces were about 12° C cooler.

Air profile temperatures near the surface were affected more by shade than by height above the surface, seedbed type, or aspect (table 2). Shade reduced maximum temperatures 6–10° C and produced more uniform temperatures with height. Air temperatures were higher near the surface (2.5 cm) and decreased with an in-

Table 2.—Profile of mean, maximum and minimum temperatures (°C) of seedbeds by aspect at the surface, and at different heights above and below the surface[1]

Location	Height (cm)	Scarified-Shaded			Scarified-Unshaded			Unscarified-Shaded			Unscarified-Unshaded		
		mean	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.
North Aspect													
Above	20.3	19.3	10.8	23.6	22.4	9.4	30.0	18.3	9.4	22.2	24.1	13.3	31.7
surface	10.2	19.5	10.8	23.9	22.9	9.4	30.6	18.1	9.4	21.7	24.4	13.3	31.7
	5.1	19.6	10.8	23.9	24.0	10.0	31.7	18.4	9.4	22.8	26.3	12.5	33.1
	2.5	20.4	10.8	25.9	25.2	10.6	33.3	19.0	10.0	25.0	28.1	13.6	35.3
Surface	U[2]	29.7	13.9	39.0	33.7	18.3	43.0	39.2	18.9	48.9	42.3	19.4	55.0
	S[2]	24.3	12.2	31.1	—	—	—	33.2	13.9	42.7	—	—	—
Below	2.5	17.3	11.1	21.1	18.7	11.1	24.8	15.1	11.4	19.7	21.3	15.6	25.3
surface	5.1	15.8	11.1	17.8	17.6	10.6	22.2	12.9	10.9	15.9	18.2	12.8	21.1
	10.2	13.8	11.1	15.0	14.9	10.6	17.5	12.0	9.7	13.1	15.2	11.1	17.2
	20.3	11.7	10.0	12.8	13.5	10.6	15.6	10.4	9.4	11.1	12.8	11.1	13.6
South Aspect													
Above	20.3	18.6	13.3	23.3	22.8	13.1	28.9	18.3	10.9	22.8	22.7	13.6	29.4
surface	10.2	18.4	13.3	22.5	23.5	12.8	29.4	18.5	10.9	23.3	23.3	13.6	30.0
	5.1	18.7	13.3	22.8	24.6	13.1	30.6	19.0	11.1	24.7	24.7	14.4	32.0
	2.5	20.0	12.8	24.4	26.0	13.6	32.5	19.7	11.1	25.9	26.2	15.0	33.9
Surface	U[2]	39.1	19.4	50.0	41.9	21.7	51.0	41.8	16.1	51.1	[3]>51.4	21.1	[3]>60.0
	S[2]	33.7	16.4	43.3	—	—	—	34.5	13.6	43.5	—	—	—
Below	2.5	19.3	12.8	23.6	23.7	15.0	29.4	17.1	11.7	20.3	22.8	13.6	26.4
surface	5.1	17.7	12.2	21.1	20.7	13.6	25.6	14.2	11.4	17.0	19.0	12.2	22.2
	10.2	15.3	11.7	17.2	17.6	11.7	21.1	12.6	10.6	13.9	15.6	11.7	17.2
	20.3	13.4	11.7	15.0	13.7	11.7	16.7	11.8	10.3	13.3	13.4	11.7	14.2

[1]*Measurements made hourly from 6 a.m. to 7 p.m., between June 15 and August 15, 1971, 1972 and 1973.*
[2]*U = Unshaded, S = Shaded.*
[3]*Maximum surface temperatures on unscarified-unshaded seedbeds exceed the range (60°C) of the instrument being used.*

crease in height to 20.3 cm. There was one seeming anomaly; air profile temperatures were generally 1–2° C higher on the north aspect.

Soil profile temperatures just below the surface were affected more by shade and depth below the surface than seedbed type and aspect (table 2). Shade reduced maximum temperatures near the surface (2.5 cm) 4° to 6° C, but was less effective as depth increased to 20.3 cm, where maximum soil temperature differences between shaded and unshaded seedbeds were 1° to 3° C. Soil profile temperatures were only slightly higher on the south aspect. Soil temperatures decreased considerably (8–12° C) as depth increased from 2.5 to 20.3 cm on both aspects.

Seedling Establishment

Germination

Germination was considerably better on the north aspect than on the south aspect (table 3). However, total germination on the north aspect for all years was only 6.1%, ranging from a high of 10.5% in 1974 to a low of 0.9% in 1971 (table 3). Germination was improved significantly in most years by scarification but not by shade. The scarification × years interaction was highly significant, indicating that there was considerable variability in germination from year to year on scarified seedbeds.

Total germination for all years on the south aspect was only 2.9%, ranging from a high of 14.5% in 1972 to a low of 0.2% in 1970 (table 3). In some years, shade significantly improved germination, and in a few years, the combination of shade and scarification significantly improved germination. All interactions between years and cultural treatments were highly significant, indicating high variability in germination among the treatments from year to year.

Survival

Survival was also better on the north aspect than on the south aspect (table 3). However total survival on the north aspect at the end of the study was only 1.4% of the viable seeds sown. Seedlings that survived through the fifth growing season generally survived to the end of the study. In most years, survival was significantly improved by scarification, by shade, and by the combination of scarification and shade. The scarification × years interaction and the differences in survival between years were also significant.

On the south aspect, total survival was only 0.2% of the viable seeds sown (table 3). Although seedlings that

Table 3.—Percent germination and survival of Engelmann spruce by aspect, seedbed treatment and year (basis number of viable seeds sown)

Year	Scarified and Shaded				Scarified and Unshaded				Unscarified and Shaded				Unscarified and Unshaded				Total			
	Germination	Survival end of- 1st yr	5th yr	study[1]	Germination	Survival end of- 1st yr	5th yr	study[1]	Germination	Survival end of- 1st yr	5th yr	study[1]	Germination	Survival end of- 1st yr	5th yr	study[1]	Germination	Survival end of- 1st yr	5th yr	study[1]
North Aspect																				
1969	21.1	10.9	7.5	6.9	12.8	7.2	3.2	3.2	4.5	1.6	1.3	0.8	0.8	0	0	0	9.8	4.9	3.0	2.7
1970	12.5	8.8	4.5	4.3	7.2	4.3	1.6	1.6	4.5	2.1	0.3	0.3	1.3	0.5	0.5	0.5	6.4	3.9	1.8	1.7
1971	1.1	0.5	0.5	0.5	2.1	2.1	0.5	0.5	0	0	0	0	0.5	0.3	0	0	0.9	0.7	0.3	0.3
1972	6.9	1.3	0.8	0.8	11.2	0.8	0	0	1.6	0.3	0	0	2.4	0.3	0	0	5.5	0.7	0.2	0.2
1973	7.2	4.0	2.1	2.1	3.5	1.3	0.3	0.3	9.6	5.9	3.5	2.9	3.2	1.9	0	0	5.9	3.3	1.5	1.3
1974	8.0	5.9	2.9	2.7	2.1	1.1	0.3	0.3	21.1	4.5	2.4	2.1	10.9	2.1	0.5	0.5	10.5	3.4	1.5	1.4
1975	9.3	3.7	0.5	0.5	8.3	3.7	0.5	0.5	4.8	2.9	1.6	1.3	1.1	0.5	0	0	5.9	2.7	0.7	0.6
1976	1.6	0.5	0.3	0.3	1.1	0.5	0.3	0.3	8.3	5.9	2.9	2.9	2.1	1.9	1.3	1.3	3.3	2.1	1.2	1.2
1977	10.7	8.3	2.4	2.4	4.8	2.4	0.3	0.3	1.3	1.1	0.3	0.3	1.1	0.5	0	0	4.5	3.1	0.7	0.7
1978	15.2	10.9	9.9	9.9	11.7	7.2	6.1	6.1	4.5	2.9	1.6	1.6	0.3	0	0	0	7.9	5.3	4.4	4.4
Aver.	9.4	5.5	3.1	3.0	6.5	3.1	1.3	1.3	6.0	2.7	1.4	1.2	2.4	0.8	0.2	0.2	6.1	3.0	1.5	1.4
South Aspect																				
1969	6.7	1.3	0.3	0.3	2.1	0	0	0	6.9	2.4	1.9	1.9	2.4	0	0	0	4.5	0.9	0.5	0.5
1970	0	0	0	0	0	0	0	0	0.8	0.3	0.3	0.3	0	0	0	0	0.2	0.1	0.1	0.1
1971	1.6	0.5	0.5	0.5	1.3	0	0	0	0.3	0	0	0	0.5	0	0	0	0.9	0.1	0.1	0.1
1972	10.9	1.9	0.8	0.8	9.6	0.5	0	0	26.9	1.1	0	0	10.7	0	0	0	14.5	0.9	0.2	0.2
1973	5.9	2.4	1.3	1.3	0	0	0	0	5.9	2.4	1.1	0.5	2.7	1.3	0	0	3.6	1.5	0.6	0.5
1974	0	0	0	0	0	0	0	0	5.6	0.3	0	0	5.1	0	0	0	2.7	0.1	0	0
1975	0.3	0	0	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0.3	0	0	0
1976	0.3	0	0	0	0	0	0	0	0.8	0.3	0	0	0	0	0	0	0.3	0.1	0	0
1977	2.7	0.3	0	0	0	0	0	0	4.3	0.3	0	0	0	0	0	0	1.7	0.1	0	0
1978	0.5	0	0	0	0.5	0	0	0	0.5	0	0	0	0	0	0	0	0.4	0	0	0
Aver.	2.9	0.6	0.3	[2]0.3	1.4	0.1	0	0	5.3	0.7	0.3	0.3	2.1	0.1	0	0	2.9	0.4	0.2	0.2

[1]*Seedling age in 1982 ranged from 5-years old (1978 germination) to 14-years old (1968 germination).*
[2]*Seedling age in 1982 ranged from 10-years old (1973 germination) to 14-years old (1969 germination).*

survived through the fifth growing season generally survived to the end of the study, there was no survival on any of the seedbed treatments for seeds sown after 1975. In those few years when seedlings survived beyond the first year, shade and the combination of shade and scarification significantly improved survival. The shade × years interaction was significant, indicating high variability between years.

Mortality

Seventy-six percent of the seedlings that germinated on the north aspect died by the end of the study (table 4). About two-thirds of the total mortality occurred the first year. On the south aspect, 95% of the seedlings were dead by the end of the study, with more than 90% of the total mortality occurring the first year.

Drought was the most significant cause of mortality on both aspects, followed by clipping by birds (table 4). On the north aspect these two factors plus frost heave and snowmold accounted for nearly 90% of the mortality. On the south aspect, drought, clipping, and heat girdle accounted for about 90% of the mortality.

Seed:Seedling Ratios

Seed:seedling ratios developed from this study have been reported previously (Alexander 1983). Therefore, only the necessary detail is repeated here.

The lowest seed:seedling ratios were on the scarified-shaded seedbeds on the north aspect. Neither shade nor scarification was as effective as the combination of shade and scarification on the north aspect. It required nearly 2.5 times as many seeds to produce a 5-year-old seedling on the scarified-unshaded and unscarified-shaded seedbeds as on the scarified-shaded seedbeds. It required nearly 13 times as many seeds on the unscarified-unshaded seedbeds to produce a 5-year-old seedling as on the scarified-shaded seedbeds (table 5).

On the south aspect, the only seed:seedling ratios established were on the scarified-shaded and unscarified-shaded seedbeds. Compared to equivalent seedbeds on the north aspect, it required more than 10 times as many seeds on scarified-shaded seedbeds and nearly 5 times as many on the unscarified-shaded seedbeds to produce a 5-year-old seedling (table 5).

Table 4.—Percent total mortality by aspect, cause and seedbed treatment (basis number of seedlings that germinated)

Cause of Mortality	Scarified-Shaded			Scarified-Unshaded			Unscarified-Shaded			Unscarified-Unshaded			Total		
	End 1st yr	End 5th yr	End study[1]	End 1st yr	End 5th yr	End study	End 1st yr	End 5th yr	End study	End 1st yr	End 5th yr	End study	End 1st yr	End 5th yr	End study
North Aspect															
Drought	9.9	14.2	14.2	8.3	9.9	9.9	15.6	20.2	20.5	7.8	10.4	10.4	41.6	54.7	55.0
Clipping	7.2	7.2	7.2	6.1	6.1	6.1	1.3	1.3	1.3	0	0	0	14.6	14.6	14.6
Frost heave	0.3	6.4	6.4	0.6	4.5	4.5	0.1	0.7	0.7	0	0.5	0.5	1.0	12.1	12.1
Snow mold	0	0.9	1.3	0	2.6	2.6	0	0.7	1.2	0	0	0	0	4.2	5.1
Washout	2.0	2.3	2.3	1.0	1.2	1.2	0	0	0	0	0	0	2.9	3.5	3.5
Freezing	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.7	0.7	0.7	0.7	0.7	1.1	1.6	1.6
Heat girdle	0.7	0.7	0.7	0.9	0.9	0.9	0.1	0.1	0.1	0	0	0	1.7	1.7	1.7
Other[2]	0.9	1.9	2.0	1.4	2.5	2.5	0.6	1.8	1.9	0	0	0	2.9	6.2	6.4
Total	21.0	33.7	34.2	18.3	27.8	27.8	18.1	25.5	26.4	8.5	11.6	11.6	65.8	98.6	100.0
South Aspect															
Drought	10.1	11.1	11.1	7.7	7.7	7.7	23.8	26.0	26.5	13.9	14.7	14.7	55.5	59.5	60.0
Clipping	7.0	7.0	7.0	0.5	0.5	0.5	10.8	10.8	10.8	1.2	1.2	1.2	19.5	19.5	19.5
Frost heave	0.5	2.2	2.4	0.5	0.9	0.9	0.5	0.5	0.5	0	0	0	1.5	3.6	3.8
Snow mold	0	0	0	0	0	0	0	0.2	0.2	0	0	0	0	0.2	0.2
Washout	1.2	1.2	1.2	0.7	0.7	0.7	0	0	0	0	0	0	1.9	1.9	1.9
Freezing	0	0.2	0.2	0	0	0	0.5	0.5	0.5	0	0	0	0.5	0.7	0.7
Heat girdle	1.0	1.0	1.0	1.7	1.7	1.7	4.8	4.8	4.8	2.6	2.6	2.6	10.1	10.1	10.1
Other[3]	0.2	0.5	0.5	0.7	0.7	0.7	1.0	1.9	1.9	0.7	0.7	0.7	2.6	3.8	3.8
Total	20.0	23.2	[4]23.5	11.8	12.2	12.2	41.4	44.7	45.2	18.4	19.2	19.2	91.6	99.3	100.0

[1]*Seedlings age at end of study (1982) varied from 5 to 14 years old.*
[2]*Includes isolation, damping off, gophers and unknown.*
[3]*Includes isolation, damping off and unknown.*
[4]*Seedlings age at end of study (1982) varied from 10 to 14 years old.*

Table 5.—Seed to seedling ratios at the end of germination, and the first, and fifth growing seasons by seedbed treatment and aspect (Alexander 1983)

Seedbed treatment	Germinating seedlings			First year survival[1]			Fifth year survival[2]		
	Mean	Range	%	Mean	Range	%	Mean	Range	%
North Aspect									
Scarified shaded	11:1	5:1 to 94:1	9	18:1	9:1 to 188:1	59	32:1	10:1 to 375:1	57
Scarified unshaded	15:1	8:1 to 94:1	6	33:1	14:1 to 188:1	47	76:1	16:1 to ∞	44
Unscarified shaded	17:1	5:1 to [3]∞	6	37:1	17:1 to ∞	45	72:1	29:1 to ∞	52
Unscarified unshaded	42:1	9:1 to 375:1	2	125:1	54:1 to ∞	34	417:1	75:1 to ∞	30
South Aspect									
Scarified shaded	35:1	9:1 to ∞	3	156:1	42:1 to ∞	22	341:1	75:1 to ∞	46
Scarified unshaded	74:1	10:1 to ∞	1	1,875:1	188:1 to ∞	4	∞		0
Unscarified shaded	19:1	4:1 to 375:1	5	144:1	14:1 to ∞	13	312:1	54:1 to ∞	46
Unscarified unshaded	46:1	9:1 to ∞	2	750:1	94:1 to ∞	6	∞		0

[1]*Ratio of germinating seedlngs to survival at the end of the first growing season.*
[2]*Ratio of seedlings alive at the end of the first growing season to seedlings alive at the end of 5 growing seasons.*
[3]*∞ = no germination or survival.*

DISCUSSION

The important factors influencing natural regeneration of Engelmann spruce after clearcutting in the central Rocky Mountains based on this study and literature reviewed by Noble (1974), are summarized in figure 10.

Natural regeneration of spruce requires sufficient viable seeds falling in microenvironments favorable for germination and survival. Variability in seed viability and dispersal was reduced in this study by artificially sowing a known number of viable seeds, allowing research efforts to concentrate on factors affecting germination and initial survival. Although the techniques used could not adequately measure the microenvironments of individual seedlings, it was possible to characterize the microenvironment of seedbeds which influenced how seedlings responded. Those factors having a major effect on the seedbed include (1) weather, (2) aspect, and (3) cultural treatments. Biotic factors (primarily clipping of seed coats by birds) did not directly affect seedbeds, but did affect regeneration success.

Weather

Threshold temperature and precipitation values in figure 10 are reasonable guides. However, the distribution of precipitation during the growing season and the time and duration of temperature extremes are also important factors that influence the threshold values.

Generally, temperature and precipitation work together, but not always. A single rainstorm of high intensity can wash away both seeds and seedlings, while unusually low midsummer temperatures can cause frosts which damage current growth of established seedlings and kill newly emerged seedlings. Both conditions occurred during the period of observation, but were relatively infrequent. Their potential for serious losses to regeneration in spruce-fir forests should not be overlooked, however (Roe et al. 1970).

The interactions of temperature and precipitation that resulted in seedling mortality from drought and frost heaving were more serious. Drought—excessive loss of moisture from soil and seedlings—generally resulting from low and/or irregular precipitation and high air temperatures for several weeks, may occur at any time during the growing season. It is most limiting to spruce regeneration and seedling survival during the period immediately following spring snowmelt. At elevations where spruce grows, high air temperatures may not contribute as much to drought induced low germination and poor seedling survival as does low and/or irregular precipitation. For example, 1971 was a poor year for germination on both aspects (0.9%), and precipitation was below average and poorly distributed. During the 6 weeks following snowmelt, the north aspect received 3.8 cm of precipitation in 8 storms, compared to the average of 8.9 cm of precipitation in 11 storms; the south aspect received 4.8 cm of precipitation in 6 storms, compared to an average of 9.6 cm in 9 storms. Mean maximum air temperatures were about 1.5° C above average on the north aspect and about average on the south aspect. In contrast, 1972 was a good year for germination on the south aspect (14%) and an average

REGENERATION CONDITIONS

	FAVORABLE		UNFAVORABLE
a	>600,000 seed/ha	SEED CROP	<100,000 seed/ha
b	North and East	ASPECT	South and West
c	Ambient air >0° C night and <25° C day; maximum surface <30° C	TEMPERATURES	Ambient air <0° C night and >25° C day; maximum surface >30° C
d	>1.25cm week	PRECIPITATION	<1.00cm week
e	Light-textured, sandy-loam	SOIL	Heavy-textured, clay-loam
f	>40% exposed mineral soil	SEEDBED	<20% exposed mineral soil
g	50-70% dead shade		<30% dead shade
h	<5 cm duff and litter		>10cm duff and litter
i	Light vegetative cover <30% non sod-forming		Heavy vegetative cover >60 % sod-forming
j	Seedings >12 weeks old by mid-Sept	SURVIVAL	Seedlings <12 weeks old by mid-Sept
k	Low population of birds and small mammals that eat tree seed and young seedlings		High population of birds and small mammals that eat tree seed and young seedlings
l	Protection from trampling		No protection from trampling
m	Fall snow cover when frost heaving conditions exist		No fall snow cover when frost heaving conditions exist
n	No late lying spring snowfields when conditions favorable to snowmold exist		Late lying spring snowfields when conditions favorable to snowmold exist

Figure 10.—Conditions favorable and unfavorable to natural regeneration of Engelmann spruce.

year on the north aspect (6%). The south aspect received 9.3 cm of precipitation in 14 storms; on the north aspect 7.6 cm of precipitation fell in 9 storms. Mean maximum air temperatures were about average on the north aspect and about 0.5° C above average on the south aspect, for the first 6 weeks after spring snowmelt.

Frost heaving—resulting from the interaction of moisture and temperature—was a serious cause of mortality, especially on the north aspect. Frost heaving occurred when soil moisture was at or near field capacity, there was no vegetational or snow cover, and day-night temperatures were alternating above and below 0° C. Seedling losses from frost heaving were recorded every year on the north aspect, but were more severe in some years than others. Frost heaving is most likely to occur during the first 2 to 3 weeks following snowmelt in the spring, and again in the fall just before permanent snow cover.

The effects of other weather factors—radiation, vapor pressure defects (VPD's), and wind—become more apparent when considered with aspect.

Aspect

This study was specifically planned to describe the environment in relation to spruce regeneration on a north and a south aspect. The study areas were only about 7.2 km apart, in the same major drainage, and at the same elevation and slope. Because of local topography, the south aspect averages slightly more precipitation (3.0 cm) during the growing season. However, the distribution patterns were very similar, and no substantial differences in wind patterns were evident, indicating that the same major air mass generally covered both aspects. The effects of net radiation, VPD, and temperature on regeneration success, therefore, were more apparent when related to aspect.

Maximum surface temperatures on all four seedbed treatments averaged from 2.2° C to 11.0° C higher on the south aspect, even though air temperatures measured at 1.37 cm above the ground either in the open or in the weather shelters averaged less than 1° C warmer on the south aspect. The higher surface temperatures on the south aspect caused greater soil temperatures at 2.5, 5.1, 10.2, and 20.3 cm below the surface. However, air temperatures at 2.5, 5.1, 10.2, and 20.3 cm above the surface were generally 1–2° C higher on the north aspect.

This anomaly of higher air profile temperatures above the surface on the north aspect occurred because the north aspect was in direct sunlight from shortly after sunrise to sunset, whereas the south aspect was shaded by late afternoon as the sun moved behind the high ridge just to the west and above the study area. The higher surface and soil temperatures, plus VPD's averaging about 8% higher on the south aspect, increased evapotranspiration rates and created a drier environment. The result was poorer germination and higher seedling mortality from drought and heat girdle—the death of stem tissue near the ground surface in newly emerged seedlings resulting from the interaction of high surface temperatures and dry soils.

Snowmelt was usually 7 to 10 days earlier on the south aspect. Early snowmelt followed by periods of low and/or irregular precipitation during the first critical weeks limited spruce regeneration success. Seedbeds changed rapidly from too cold and wet for germination to too hot and dry for most seedlings to emerge. Those seedlings that did emerge could not survive the hot, dry weather. These later circumstances were largely responsible for the lack of any survival on the south aspect for seeds sown after 1973.

The greater net radiation of at least 8% on the south aspect was largely responsible for the higher seedbed surface temperatures and vapor pressure defects. However, high light intensity (solar radiation) was not directly limiting to regeneration success. Few seedlings died from insolation (solarization) on either aspect.

Seedbed Treatments

On the north aspect, scarification improved the microenvironment of the seedbeds for germination and survival, probably by increasing available soil moisture. Shade also improved the seedbed microenvironment for survival by reducing temperatures, but only in those years when snowmelt was followed by periods of regular summer precipitation. On the south aspect, shade and the combination of shade and scarification improved the seedbed microenvironment for both germination and survival. Eis (1970), working in spruce-fir forests in the interior of British Columbia, found that available soil moisture at a depth of 5 cm was substantially higher in mineral soil than in humus. Day (1963), working in Alberta, reported that shade reduced water losses from both seedlings and soil. Results of this study generally agree with this earlier work. The layer of organic matter on the north aspect was 7 cm or more thick, and scarification most likely increased available soil moisture. In contrast, the organic layer on the south aspect was less than 5 cm thick, and scarification was less effective. However, because of high surface temperatures, it is likely that scarification would be less effective on south aspects, regardless of the thickness of the organic layer. The fact that shade was essential to any regeneration success on the south aspect and improved survival on the north aspect reemphasizes the importance of reducing water losses from soil and seedlings in clearcut openings in spruce-fir forests.

Biotic Factors

The significant biotic factors affecting regeneration were clipping of cotyledons on newly germinated seedlings, and snowmold. Initially rodents were suspected of doing the clipping; but by periodic trapping inside the exclosures, and from visual and photographic evidence, it was determined that grey-headed juncos (*Junco caniceps* Woodhouse) were responsible (Noble and Shepperd 1973). Snowmold fungus (*Herpotrichia nigra* Hartig) was largely confined to the north slope. It caused more damage than mortality, but it occurred every year on those plots that were shaded and in depressions where snow normally accumulated and melted slowly. Snowmold also occurred on other plots in those years when snowfall was heavy or when weather retarded spring snowmelt.

Other biotic factors causing seed and seedling losses such as damping-off fungi, insects, and needlecast were not limiting to regeneration success.

Seed:Seedling Ratios

A reasonable stocking goal for Engelmann spruce is 1,976 seedlings per hectare at age 5 years (Alexander and Edminster 1980). This is more than required for adequate stocking, but necessary to achieve uniform spacing, allow for possible future mortality, and provide options in selecting crop trees in subsequent thinnings. Numbers of seeds, based on seed to 5-year seedling ratios in table 5, required to produce this stocking level under different seedbed conditions on north and south aspects are shown in table 6.

Table 6.—Number of viable seeds per ha required to produce 1,976 five-year-old Engelmann spruce seedlings in relation to seedbed treatments and aspect[1] (Alexander 1983)

Seedbed treatment	North Aspect	South Aspect
Scarified-shaded	63,232	673,816
Scarified-unshaded	150,176	[2]∞
Unscarified-shaded	142,272	616,512
Unscarified-unshaded	823,992	∞

[1]*Data presented are based upon the exclusion of seed-eating mammals. If these animals are not excluded, numbers of seed required should be increased by 50% to 100%.*
[2]*∞ = no survival.*

Data presented in tables 5 and 6 are minimums, based upon the exclusion of seed-eating small mammals, but not birds that consume tree seeds. All spruce-fir forests support populations of these small mammals; and any disturbance that initiates understory plant succession probably favors a buildup of these populations, particularly if slash and other downed materials are present to provide cover. Although these mammals consume considerable amounts of seed, the magnitude of the loss is not known in the central Rocky Mountains. However, losses to seed-eaters are more important in years of poor seed production, or years when populations of seed-eating mammals are high.

CONCLUSIONS

Clearcut openings 1 to 2 ha on north aspects, in spruce-fir forests, in the central Rocky Mountains can be successfully regenerated naturally from seed with the aid of cultural treatments. Based on a stocking goal of 1,976 5-year-old seedlings per hectare, and previously published data on seed production (Alexander et al. 1982) and seed dispersal (Alexander and Edminster 1983) scarified-shaded seedbeds should restock within a 5-year period, but may require more than one good seed year.[3] It will require a number of good seed years to restock scarified-unshaded and unscarified-shaded seedbeds, and it is not likely to be accomplished within a 5-year period. Unscarified-unshaded seedbeds in small clearcut openings on north aspects are not likely to restock adequately within a 20-year period. On south aspects, small clearcut openings are not likely to restock adequately, regardless of cultural treatments, in a reasonable amount of time. They will have to be regenerated with different cutting methods that either take advantage of advanced reproduction or provide overstory protection for new natural or planted reproduction.

Weather variables (i.e., ambient air temperature, precipitation, wind, vapor pressure deficit) and net radiation are interrelated and important for describing microclimate conditions. Microclimatic conditions near the surface of small forest openings, on comparable high-elevation north and south aspects in the Colorado Rockies are quite different, however; and standard weather measurements of air temperature, precipitation, and wind do not adequately indicate those differences. Better indicators are vapor pressure deficits and net incident radiation. Additional factors affected by microclimate and aspect in forest openings at high elevations that should be better quantified include evapotranspiration rates and soil-plant-water relationships.

[3]*A good seed year produces 247,000 to 617,500 sound seeds per hectare under uncut stands surrounding the cleared opening.*

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Table A-1.—Mean hourly maximum, minimum and mean air temperatures (°C) by aspect during the growing season for the years 1969-1982

Year	June[1]			July			August			September			October[2]			Seasonal		
	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean
North Aspect																		
1969	11.4	0.2	4.7	19.5	6.7	11.8	19.2	6.4	12.1	12.7	1.1	5.6	1.6	-8.3	-4.2	12.9	1.2	5.9
1970	18.5	5.6	12.0	18.4	5.3	11.5	17.6	5.5	10.8	10.8	-1.6	4.1	5.3	-4.5	-0.1	14.1	2.1	7.7
1971	19.1	6.2	13.0	18.6	5.4	12.1	17.4	4.0	10.1	10.8	-1.7	4.4	7.3	-3.9	1.5	14.7	2.0	8.2
1972	15.9	2.7	9.1	18.9	4.8	11.9	16.8	3.9	9.8	11.6	1.1	6.1	—	—	—	15.8	3.1	9.2
1973	15.4	2.4	9.1	15.9	3.6	9.5	16.7	4.2	9.9	10.6	-1.1	4.4	—	—	—	14.7	2.3	8.2
1974	15.6	3.1	9.7	16.8	4.3	10.2	16.5	3.4	9.8	12.1	-0.4	5.6	7.0	-2.8	1.4	13.6	1.6	7.3
1975	14.7	-1.2	7.1	18.1	4.2	10.7	16.9	3.3	10.0	12.3	0.1	5.7	7.7	-5.4	0.9	13.9	0.2	6.9
1976	13.6	0.5	7.2	19.1	5.1	11.9	15.7	3.1	9.1	11.4	0.2	5.4	—	—	—	14.9	2.2	8.4
1977	18.6	4.6	11.7	17.7	5.8	12.0	16.9	5.1	10.5	13.7	1.2	6.9	5.9	-4.7	0.5	14.6	2.4	8.3
1978	18.2	5.9	12.2	20.2	5.2	12.8	16.8	2.7	9.4	13.1	-0.2	6.2	9.4	-2.1	3.2	15.5	2.3	8.8
1979	17.1	3.1	10.6	19.1	4.4	11.6	16.4	4.0	9.7	15.7	2.3	8.4	7.9	-3.6	2.1	15.2	2.1	8.4
1980	—	—	—	19.5	5.2	12.2	16.8	3.4	9.8	13.7	0.7	6.9	7.7	-3.5	1.7	14.4	1.5	7.7
1981	18.7	4.3	11.6	17.9	4.9	11.1	16.3	2.8	9.1	13.4	0.9	6.6	6.9	-1.4	2.1	14.5	2.3	8.1
1982	—	—	—	17.3	3.9	10.4	16.9	4.3	10.1	10.6	0.1	4.9	—	—	—	14.9	2.8	8.4
Aver.	16.4	3.1	9.8	18.3	4.9	11.4	16.9	4.0	10.0	12.3	0.2	5.8	6.7	-4.0	0.9	14.1	1.6	7.6
South Aspect																		
1969	11.5	1.6	5.2	20.0	7.7	13.2	20.5	7.7	13.0	14.4	2.7	7.5	2.1	-7.4	-2.9	13.7	2.4	7.2
1970	18.2	7.1	12.2	19.2	6.4	11.9	18.9	7.2	12.0	12.0	-0.1	5.5	6.2	-3.1	0.4	14.9	3.5	8.4
1971	19.8	6.7	12.5	18.4	6.2	11.5	18.2	5.6	10.8	11.0	-1.6	4.3	8.4	-3.2	2.0	15.2	2.8	8.2
1972	16.0	3.8	9.6	19.6	6.3	12.4	17.6	5.6	10.7	12.1	2.1	6.6	—	—	—	16.3	4.4	9.8
1973	15.7	3.8	9.6	17.7	5.6	11.0	18.3	6.7	11.8	12.6	1.4	6.7	—	—	—	16.1	4.4	9.8
1974	16.6	4.4	10.1	17.6	5.9	10.8	17.3	5.2	10.6	13.2	1.1	6.5	7.8	-1.2	2.2	14.5	3.1	8.1
1975	16.7	2.3	9.7	19.2	6.6	12.1	17.7	5.3	11.1	13.2	1.8	6.9	8.7	-3.5	2.3	15.1	2.5	8.4
1976	12.4	0.7	6.8	18.5	6.3	11.9	15.6	4.1	9.3	11.1	1.2	5.6	—	—	—	14.4	3.1	8.4
1977	17.9	5.2	11.2	17.7	6.1	11.4	15.9	5.3	10.1	12.9	1.8	6.7	5.1	-4.6	0.2	13.9	2.7	7.9
1978	18.9	7.7	13.4	21.5	8.3	14.6	17.6	5.1	10.8	13.5	1.6	7.1	10.4	-1.1	3.8	16.4	4.4	10.0
1979	19.5	6.1	12.8	20.1	6.9	12.8	17.3	6.4	11.0	17.3	4.6	10.2	10.2	-0.7	4.3	16.9	4.7	10.2
1980	—	—	—	20.9	8.2	14.1	17.7	5.6	11.0	14.9	2.9	8.4	8.7	-1.8	2.7	15.6	3.7	9.1
1981	16.6	3.4	9.8	16.8	4.9	10.3	17.1	5.0	10.3	14.7	3.0	7.9	7.4	0.0	3.2	14.6	3.3	8.3
1982	—	—	—	18.1	6.3	11.7	17.6	6.8	11.2	11.6	2.2	6.4	—	—	—	15.8	5.1	9.8
Aver.	17.8	4.4	10.2	18.9	6.6	12.1	17.7	5.8	11.0	13.2	1.8	6.9	7.5	-2.7	1.8	14.8	3.2	8.4

[1]*June averages are based upon measurements taken during part of the month following activation of weather station which varied from June 3 to June 30, depending upon the time of snowmelt.*

[2]*October averages are based upon measurements taken during part of the month preceding deactivation of weather station which varied from October 1 to October 30, depending upon time of snowfall.*

Table A-2.—Mean monthly precipitation (cm) during the growing season by aspect for the years 1969-1982

Year	Total months record	June	July	Aug.	Sept.	Oct.	Seasonal Total	Seasonal Aver.
North Aspect								
1969	4	13.26	3.76	5.74	5.92	-	28.68	7.17
1970	5	0.90	4.60	7.24	9.50	0	22.24	4.45
1971	5	0.68	3.12	4.42	5.26	4.12	17.60	3.52
1972	4	5.18	2.41	7.82	6.96	-	22.37	5.59
1973	4	2.79	10.72	4.01	4.68	-	22.20	5.55
1974	5	8.46	8.86	2.26	3.25	4.19	27.02	5.40
1975	5	0.61	5.05	5.69	3.58	5.05	19.98	4.00
1976	4	4.44	6.25	6.63	8.71	-	26.03	6.51
1977	5	2.97	11.00	6.27	4.44	5.33	30.01	6.00
1978	4	0	2.36	2.34	1.73	-	6.43	1.61
1979	5	0.53	4.62	6.48	1.19	2.01	14.83	2.97
1980	4	0	3.99	4.90	3.91	0.08	12.88	3.22
1981	5	1.12	8.20	5.84	3.91	1.04	20.11	4.02
1982	3	0	1.83	6.55	5.38	-	13.77	4.60
Total	62	40.94	76.77	76.19	68.42	21.82	284.18	
Aver.	4.43	3.40	5.48	5.44	4.89	2.73	21.94	4.58
South Aspect								
1969	4	14.53	5.16	5.61	9.12	-	34.42	8.60
1970	5	0.43	2.92	8.99	9.02	0.05	21.41	4.28
1971	5	0.68	4.12	7.21	7.32	3.23	22.56	4.51
1972	4	6.45	2.87	7.85	8.72	-	25.89	6.47
1973	4	4.01	9.35	3.30	6.83	-	23.49	5.87
1974	5	11.25	8.41	2.36	4.14	4.80	30.96	6.19
1975	5	0.25	5.79	4.25	2.46	6.45	19.20	3.84
1976	4	5.13	4.27	6.35	9.68	-	25.43	6.35
1977	5	1.98	8.61	7.47	4.88	6.09	29.03	5.81
1978	4	0.36	2.79	3.02	2.44	-	8.61	2.15
1979	5	0.94	4.19	9.58	1.30	2.87	18.88	3.78
1980	4	-	8.15	5.77	6.20	0.36	20.48	5.12
1981	5	2.79	7.24	4.19	6.27	1.47	21.96	4.39
1982	3	-	3.25	10.64	6.66	-	20.55	6.86
Total	62	48.80	77.12	86.59	85.04	25.32	322.87	
Aver.	4.43	4.07	5.51	6.18	6.07	3.16	24.99	5.21

Table A-3.—Average daily maximum, minimum and mean vapor pressure deficits (mm Hg) by aspect during the growing season for the years 1968-1982

Year	June			July			August			September			October			Seasonal		
	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean
North Aspect																		
1969	12.43	2.69	9.26	14.75	8.02	12.00	16.42	3.84	10.44	10.52	5.25	7.46	5.35	2.51	4.03	11.89	4.46	8.64
1970	14.19	9.13	11.66	13.14	2.78	10.48	13.97	3.45	8.15	7.66	2.30	5.23	5.71	2.43	3.53	10.93	4.02	7.81
1971	13.14	6.89	10.42	10.87	5.88	8.74	12.62	5.56	9.53	8.85	1.81	6.51	8.68	2.15	6.12	10.83	4.46	8.26
1972	9.00	7.65	8.15	11.27	9.31	10.16	12.10	6.09	9.02	8.51	0.95	5.31	-	-	-	10.22	6.00	8.16
1973	10.76	3.37	7.83	11.64	0.76	6.78	10.50	6.32	8.20	10.43	0.97	7.12	-	-	-	10.83	2.86	7.48
1974	16.12	3.82	12.35	13.32	5.67	10.13	11.09	9.01	10.42	12.08	4.71	8.50	8.13	2.68	5.26	12.15	5.18	9.33
1975	13.59	5.98	8.83	15.73	9.48	12.03	15.77	5.18	9.52	13.67	5.24	8.47	8.80	1.83	6.35	13.51	5.54	9.04
1976	15.60	1.71	9.73	14.55	8.24	10.80	13.43	6.78	10.27	9.97	0.68	5.95	-	-	-	13.88	4.35	9.19
1977	16.33	10.90	13.28	14.76	2.98	10.74	15.47	5.89	11.10	12.27	6.63	9.39	4.13	1.32	2.55	12.59	5.54	9.41
1978	14.07	10.47	11.91	17.63	11.60	14.08	12.62	7.11	10.40	12.99	6.17	9.26	8.57	5.85	6.82	13.18	8.24	10.49
1979	14.64	1.38	9.46	15.47	9.00	12.32	15.69	0.88	9.22	15.02	6.83	9.88	9.80	0.88	6.11	14.12	3.79	9.40
1980	-	-	-	16.00	7.29	11.69	14.96	5.71	11.28	9.46	7.02	8.35	9.80	2.07	6.56	12.56	5.52	9.47
1981	11.75	5.24	9.07	15.77	7.93	12.31	12.80	5.67	9.21	10.33	4.16	7.67	-	-	-	12.66	5.75	9.56
1982	-	-	-	14.27	4.69	10.56	14.08	8.24	10.18	8.85	5.80	7.32	9.54	2.58	6.04	11.68	5.33	8.52
Aver.	13.47	5.77	10.16	14.27	6.69	10.92	13.68	5.70	9.78	10.76	4.18	7.60	7.75	2.43	5.34	11.97	4.95	8.76
South Aspect																		
1969	12.52	2.85	9.52	16.55	11.26	13.43	18.06	6.76	13.12	13.32	6.93	9.57	7.36	2.94	5.14	13.56	6.15	10.16
1970	14.47	11.45	12.96	14.76	4.32	11.78	15.27	3.84	9.43	7.96	3.14	6.47	8.38	3.07	4.87	12.17	5.17	9.10
1971	14.18	10.02	12.02	14.34	5.50	10.18	12.70	5.97	10.60	11.69	2.52	8.42	10.47	2.66	7.55	12.68	5.33	9.75
1972	9.80	8.25	8.88	13.26	10.47	11.68	14.08	8.54	10.80	10.61	0.73	5.85	-	-	-	11.94	7.00	9.30
1973	10.87	2.39	7.74	14.37	1.91	8.89	10.87	7.29	8.71	11.60	0.82	7.74	-	-	-	11.93	3.10	8.27
1974	15.93	3.67	12.09	13.43	5.43	9.56	15.07	8.48	11.00	12.43	4.27	8.05	8.43	3.02	5.23	13.06	4.97	9.19
1975	14.88	5.12	8.56	19.15	11.26	13.23	14.07	6.17	9.57	15.67	4.05	9.01	9.46	1.50	6.71	14.65	5.62	9.42
1976	14.57	1.08	9.71	13.25	9.67	11.37	13.27	4.32	10.76	11.26	0.97	8.01	-	-	-	13.09	4.01	9.96
1977	15.42	10.33	12.25	13.79	2.99	9.91	14.02	5.02	10.47	12.70	5.92	8.99	1.68	0.90	1.12	11.52	5.03	8.55
1978	13.60	10.52	11.99	19.30	11.18	15.10	13.43	7.14	11.39	14.27	5.54	10.92	9.84	6.44	7.91	14.09	8.16	11.46
1979	14.96	13.33	13.55	15.67	9.82	13.14	14.62	0.17	8.73	15.73	7.51	10.77	11.49	0.33	7.00	14.49	6.23	10.64
1980	-	-	-	16.08	5.69	12.70	15.26	6.59	11.63	12.01	7.97	9.79	12.17	5.30	8.70	13.88	6.39	10.70
1981	12.11	4.20	8.73	16.33	7.42	12.12	13.67	6.57	10.74	11.39	4.27	8.41	-	-	-	13.38	5.62	10.00
1982	-	-	-	14.55	4.02	10.50	15.02	9.10	11.26	10.60	6.34	8.47	10.43	2.98	6.62	12.65	5.61	9.21
Aver.	13.61	6.93	10.67	15.34	7.21	11.68	14.24	6.00	10.59	12.23	4.36	8.60	8.97	2.91	6.08	12.88	5.48	9.52

Table A-4.—Average daily maximum, minimum and mean incident radiation (ly) by aspect during the growing season for the years 1969-1982

Year	June			July			August			September			October			Seasonal		
	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean
North Aspect																		
1969	589	493	533	695	571	632	593	428	506	506	353	407	264	218	247	529	413	465
1970	699	531	636	690	472	579	540	381	448	471	344	413	432	206	305	566	387	476
1971	781	370	593	708	589	644	622	369	496	533	402	468	404	301	340	610	406	508
1972	759	588	639	710	564	657	578	385	468	432	363	402	388	191	274	573	418	488
1973	677	549	622	705	377	552	550	402	474	454	331	405	326	259	286	542	384	468
1974	693	510	622	696	477	547	584	495	537	510	428	470	442	127	297	585	407	495
1975	701	538	627	624	553	587	610	440	522	540	329	441	444	233	346	584	419	505
1976	696	580	631	601	442	539	543	413	496	503	253	364	370	296	337	543	397	473
1977	704	518	590	701	397	555	518	382	450	474	385	430	385	250	317	556	386	468
1978	761	504	658	648	579	606	609	511	538	482	353	413	421	216	334	584	433	510
1979	636	572	613	618	513	547	496	389	420	473	388	438	421	240	333	529	420	470
1980	768	680	717	654	489	583	544	382	491	479	432	456	441	193	338	577	435	517
1981	703	606	657	533	472	503	523	339	444	432	368	397	308	228	282	500	403	456
1982	660	487	564	596	482	546	454	348	390	339	285	308	348	264	303	479	373	422
Aver.	702	538	622	656	498	577	555	405	477	473	358	415	385	230	310	554	406	480
South Aspect																		
1969	585	488	528	690	582	638	622	469	546	579	425	485	382	303	337	572	453	507
1970	691	526	630	685	472	585	577	416	484	569	429	492	557	275	414	616	424	521
1971	773	368	587	731	600	651	643	411	531	626	486	557	541	434	464	663	460	558
1972	751	584	633	734	575	665	607	429	504	538	413	480	500	276	370	626	455	530
1973	670	546	616	700	381	557	588	488	511	519	412	482	453	334	392	586	432	512
1974	686	507	616	689	487	551	625	522	572	594	517	560	554	183	393	630	443	538
1975	694	533	621	624	571	593	645	471	564	622	386	526	573	337	468	632	460	554
1976	689	570	623	597	457	544	593	450	536	574	316	431	513	435	472	593	446	521
1977	696	513	585	724	405	571	544	417	486	542	452	514	535	344	432	608	426	518
1978	753	501	651	660	583	612	639	546	580	551	427	492	543	317	454	629	475	558
1979	630	568	607	617	510	552	520	416	453	567	484	522	421	240	450	551	444	517
1980	764	692	710	666	489	590	571	426	530	598	522	560	569	269	457	634	480	569
1981	695	602	650	544	469	509	559	370	490	523	432	474	445	317	385	553	438	502
1982	656	482	559	595	492	549	476	388	419	410	335	373	450	382	409	517	416	462
Aver.	695	534	615	661	505	583	586	444	515	558	431	496	503	318	421	600	446	526

Table A-5.—Mean daily and peak gust wind velocity (km/hr) by aspect during the growing season for the years 1970–1982

	June		July		August		September		October		Total		Average	
Year	HR	PG	HR	PG	HR	PG	HR	PG	HR	PG	HR	PG	HR	PG
North Aspect														
1970	-	-	-	-	2.2	5.5	3.1	8.4	2.1	5.5	7.4	19.4	2.5	6.4
1971	-	-	3.9	9.5	3.5	7.7	3.7	10.1	3.4	9.2	14.5	36.5	3.6	9.1
1972	4.2	11.1	3.5	8.8	2.7	6.8	2.9	8.4	-	-	13.3	35.1	3.3	8.8
1973	3.5	9.2	3.4	7.4	2.9	6.6	2.9	7.6	-	-	12.7	30.8	3.2	7.7
1974	3.5	9.8	2.6	7.2	2.7	8.8	2.6	8.2	2.9	8.5	14.3	42.5	2.9	8.5
1975	4.4	10.9	2.6	6.9	2.2	7.1	1.9	6.8	2.7	7.9	13.8	39.6	2.8	7.9
1976	4.2	11.8	2.7	7.4	2.4	6.8	1.8	5.2	-	-	11.1	31.2	2.8	7.8
1977	3.4	8.7	2.6	6.8	2.4	6.6	2.9	7.7	-	-	11.3	29.8	2.8	7.4
1978	3.9	10.1	2.1	7.2	2.1	7.1	1.9	6.8	2.2	7.9	12.2	39.1	2.4	7.8
1979	2.7	9.7	1.8	6.6	1.6	6.4	1.6	6.3	1.9	8.0	9.6	37.0	1.9	7.4
1980	-	-	2.6	6.8	2.2	6.8	3.1	6.8	1.9	5.0	9.8	25.4	2.4	6.4
1981	2.2	6.1	0.8	2.9	0.8	2.1	0.6	1.9	0.5	2.1	4.9	15.1	1.0	3.0
1982	-	-	1.6	3.9	1.0	2.6	1.5	3.1	1.3	4.5	5.4	14.1	1.4	3.5
Total	32.0	87.4	30.2	81.4	28.7	80.9	30.5	87.3	18.9	58.6	140.3	395.6		
Aver.	3.6	9.7	2.5	6.8	2.2	6.2	2.4	6.7	2.1	6.5	12.8	35.9	2.6	7.2
South Aspect														
1970	-	-	-	-	1.8	5.8	4.2	11.2	4.0	10.0	10.0	27.0	3.3	9.0
1971	-	-	3.5	10.1	1.9	6.8	4.2	13.2	4.2	13.8	13.8	43.9	3.4	11.0
1972	3.7	15.6	3.5	11.4	2.9	8.5	4.3	14.6	-	-	14.4	50.1	3.6	12.5
1973	5.3	15.1	3.5	10.1	3.5	10.3	4.5	11.6	-	-	16.8	47.1	4.2	11.8
1974	4.4	12.4	2.9	9.0	3.7	12.1	3.7	12.1	3.7	11.4	18.4	57.0	3.7	11.4
1975	5.3	16.7	2.6	8.7	2.7	10.5	2.6	9.8	3.4	11.4	16.6	57.1	3.3	11.4
1976	5.5	17.4	2.9	9.0	2.9	9.3	2.6	8.2	-	-	13.9	43.9	3.5	11.0
1977	3.7	12.4	2.4	9.2	3.2	11.6	4.3	14.5	-	-	13.6	47.7	3.4	11.9
1978	3.9	13.7	3.1	11.6	3.1	11.2	2.9	10.8	4.2	13.8	17.2	61.1	3.4	12.2
1979	2.7	11.9	2.4	9.7	1.9	9.3	2.4	9.2	3.5	12.7	12.9	52.8	2.6	10.6
1980	-	-	3.9	11.1	4.0	11.6	4.5	13.2	4.2	10.0	16.6	45.9	4.2	11.5
1981	3.5	9.3	1.4	4.3	1.3	3.7	1.4	4.5	1.6	4.5	9.2	26.3	1.8	5.3
1982	-	-	3.7	7.1	1.1	3.4	1.3	4.2	2.6	8.2	8.7	22.9	2.2	5.8
Total	38.0	124.5	35.8	111.3	34.0	114.1	42.9	137.1	31.4	95.8	182.1	582.8		
Aver.	4.2	13.8	3.0	9.3	2.6	8.8	3.3	10.5	3.5	10.6	16.6	53.0	3.3	10.6

Alexander, Robert R. 1984. Natural regeneration of Engelmann spruce after clearcutting in the central Rocky Mountains in relation to environmental factors. USDA Forest Service Research Paper RM-254, 17 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Successful natural regeneration of Engelmann spruce in small clearcut openings depends on weather and aspect and is modified by cultural treatments. Small clearcut openings (1–2 ha) can be successfully regenerated on north aspects with mineral soil seedbeds and shade. On south aspects, shade is absolutely essential for any survival. However, successful natural regeneration is not likely regardless of cultural treatments. Drought is the most serious cause of mortality; but clipping by birds, frost heaving (north aspect), heat girdle (south aspect), and snowmold (north aspect) caused significant losses.

Keywords: *Picea engelmannii*, Engelmann spruce, natural regeneration, environmental factors

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Rocky Mountains

Southwest

Great Plains

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Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526

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